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Experimental investigation of resilience and pressure management in water distribution networks

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Abstract

An extensive experimental investigation into the pressure management and resilience of three water distribution network configurations is conducted including: fixed topology zones with fixed outlet pressure reducing valves (PRV), fixed topology zones with flow modulating PRVs, and a dynamic topology. Hydraulic data (128S/s) captures the network behaviour under normal conditions and failure, including artificial bursts generated by operating hydrants and a real burst that affected 8,000 properties. Under normal operation, a dynamic topology lowered pressure by 3.1% over a fixed topology with flow modulating PRVs. A dynamic topology maintained the supply of 1,400 properties during the real burst incident.

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Keywords: Dynamic topology; Water Distribution Networks; Resilience; Optimization

1. Introduction

A common objective for water companies around the world is the provision of a satisfactory level of customer service and an efficient operation that complies with regulations. One of the major losses of revenue and resources for water companies comes from leakage. In the UK, the reduction of leakage is a priority enforced by the economic regulator, Ofwat. The deterioration of aging pipelines is a major contributor to leakage, and many pipelines in use were installed in the Victorian era. Financial, logistical and operational constraints mean that pipe replacement must be carried out in stages and prioritized based on the oldest or most leaking parts of the network. Another major contributor to leakage is the water pressure [1], and pressure management strategies are one of the most efficient methods for reducing pressure and therefore leakage [2]. Water companies that are committed to reducing leakage will therefore be actively pursuing both leakage localization and pressure management activities.

A number of methods exist for identifying leakage. The most established method is sectorization [3]. This involves the permanent closure of isolation valves in the WDN to create discrete zones, commonly called district metered areas (DMA). The closed isolation valves are therefore commonly called boundary valves (BV). A flow meter is then installed at each DMA inlet and outlet. By measuring the flow during times of low customer demand (such as at

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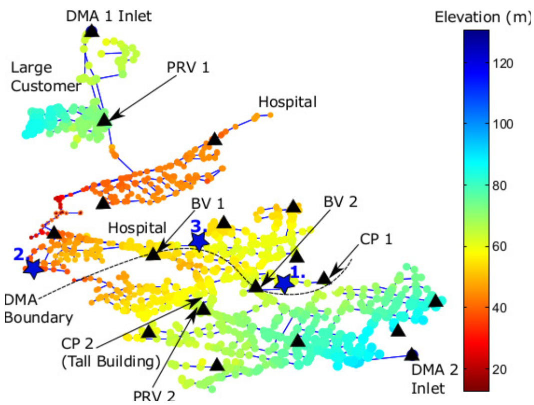
night), an estimation for leakage can be made, and DMAs prioritized for repair. Whilst the DMA has proved to be highly successful in reducing leakage in the UK [4], its implementation has not been without drawbacks created as a consequence of permanently closing boundary valves. These disadvantages include reduced resilience to failure because fewer independent supply routes exist between the customer and sources, water quality issues due to the stagnation of water at artificially created dead ends, and suboptimal pressure management [5]. Another problem with the DMA is the manual response undertaken in the event of failure. Boundary valves are sometimes opened in order to maintain supply during failure. This requires planning and time to travel to the boundary valve. Since dirty water builds up at the closed boundary valves, this approach also poses a threat to water quality.

In [6], a number of alternative technologies for leak identification and localization are reported on. These are categorized into three main groups: correlating noise loggers, multi-parameter logging, and advanced hydraulic modeling. Correlative noise loggers are installed in clusters and identify and locate leakage by monitoring noise levels. It was reported that Thames Water reduced their nightline by 22% using this method, but its widespread installation would be impractical due to the costs involved. Nevertheless, one example of an extensive deployment of noise loggers is in the city of Abu Dhabi, UAE. Multi-parameter logging involves the installation of loggers capable of measuring flow, pressure and noise simultaneously, at discrete locations. This facilitates the detection of leakage and bursts at low demand hours by analyzing the different measurements against reference values. Thames Water was again reported as having investigated this technology. Advanced hydraulic models are also being promoted for leakage identification, although there are no reports on real case studies that have been successful on a large scale. A summary of other methods developed in academia can be found in [7]. Whilst alternative methods exist for leak localization, the DMA remains one of the most well understood and cost efficient approaches currently available.

A number of methods also exist for undertaking and optimizing pressure management. Due to the widespread implementation of DMAs, pressure management options are typically installed in conjunction with DMAs. Furthermore, as pointed out in [8], the installation of a control valve should control a discrete zone with no uncontrolled flow paths into the zone. The DMA aids in pressure management implementation by forming a boundary where flow is not breached. Pressure management is undertaken by installing a pressure reducing valve (PRV) at the DMA inlet. DMAs typically have just a single inlet, although multi-feed DMAs also exist. The PRV reduces pressure downstream and throughout the DMA subject to a minimum allowable pressure threshold that exists to maintain a good level of customer service. Leakage is therefore reduced within the DMA. A number of different control options exist for the PRV operation in order to further reduce or optimize pressure subject to the minimum allowable pressure. Some of these pressure management options are explored in this paper, as outlined in section 2.

An area of research that has had little focus is how different control options for pressure management perform in terms of average zone pressure (AZP) reductions as well as resilience to failure. As outlined above, a water company is committed to providing an acceptable level of customer service, and pressure management schemes should not interfere with this objective. It is well known however that reducing network pressure can also reduce a network's resilience to failure. The purpose of this paper is to investigate this relationship. We experimentally investigate the performance of three different forms of pressure and network management using a real, operational WDN where an experimental site has been set up with pioneering developments in sensing and control technology. These configurations include fixed outlet (FO) PRVs operating on a closed, fixed DMA topology, flow modulating (FM) PRVs operating on a closed, fixed DMA topology, and flow modulating PRVs operating on a dynamic DMA topology [9]. The network configurations are tested for an extended period to assess the network's average zone pressure (AZP) for each configuration. Pressure is monitored at 128S/s [10] in order to precisely capture the network's behaviour during normal operation and a number of failure events. The failure events include the artificial generation of bursts by operating fire hydrants (see Figure 1b) and a real burst incident that occurred upstream of the network where the experimental programme is based during the operation of a dynamic topology. We observe that the operation of a dynamic topology results in AZP reductions of 3.1% or $1.3mH_2O$ compared to optimally controlled flow modulating PRVs on a closed DMA topology. Improvements in network resilience to the artificial bursts are also observed when operating a dynamic topology compared to the other configurations. During the real burst incident, the operation of the dynamic topology successfully facilitated 1,400 properties maintaining their supply that would otherwise have been without water.

The remainder of this paper is organized as follows. Section 2 discusses the different configurations of network that are experimentally investigated. Section 3 describes the operational network and the experimental investigation.



(a) Overview of the experimental programme

(b) Artificial bursts generated by operating fire hydrants

Fig. 1: (a) Elevation plot of the experimental programme network and its schematic, InfraSense TS locations (black triangle), and artificial burst locations (blue star) created by operating fire hydrants and (b) a photograph of the artificial bursts generated by operating fire hydrants

Section 4 reports on the hydraulic data showing the performance of pressure management. Section 5 reports on the hydraulic data showing the resilience to failure. In section 6 we outline some final conclusions and recommendations for future work.

2. Pressure Management in Water Distribution Networks

Three different forms of pressure management are investigated experimentally in this paper: fixed outlet (FO) PRVs operating on closed topology DMAs, flow modulating (FM) PRVs operating on closed topology DMAs, and flow modulating PRVs operating with a dynamic DMA topology. We refer to these as configuration 1, 2 and 3 respectively in some parts of the paper.

2.1. Fixed Outlet PRV (Configuration 1)

A fixed outlet pressure is the most common form of PRV control. This is typically undertaken using a hydraulic feedback loop on the PRV, making it a highly reliable control approach. The outlet pressure is generally chosen to ensure there is adequate pressure in the network at times of peak demand. Adequate pressure in the network can be verified by checking that pressure at the critical point of the network is above the minimum allowable pressure. The critical point is the point in the network where pressure is closest to the minimum allowable pressure. It may be a point with higher elevation than other points, or it may be at the extremity of the DMA, where a large amount of head loss occurs along the route to this point. It can also be a point where the minimum allowable pressure is higher than other nodes, for example at tall building, or critical customers. A disadvantage of operating fixed outlet PRVs is that there will often be excess pressure in the network, which results in higher leakage. This is most apparent at night when demand is minimal and frictional energy losses are low.

2.2. Flow Modulating PRV (Configuration 2)

Flow modulation control uses a locally measured flow at the PRV, which is an estimate of demand and therefore energy losses in the DMA, to vary the PRV outlet pressure accordingly. The PRV modulates the pressure based on this flow reading using a look up table designed to provide higher pressures during high demand periods. This approach therefore addresses the disadvantage of excessive pressure in the network produced by fixed outlet PRVs. The look up table can be produced statistically [11], using a hydraulic model and optimization method [12], or in an adhoc way using engineering judgment and a knowledge of the DMA. A major advantage of operating flow modulation PRVs over fixed outlet PRVs is that they can react to some types of network failure where an increase in demand is measured, such as fire flow or bursts.

2.3. Dynamic Topology (Configuration 3)

Operating DMAs with a dynamic topology and in conjunction with flow modulation PRV control is another approach to pressure and network management [5,9]. In section 1, a number of disadvantages were associated with the permanent closure of isolation valves to form DMAs. By introducing a dynamic topology to DMAs, these disadvantages can be eliminated. More specifically:

- Pressure management is more efficient because lower frictional energy losses occur in networks with higher redundancy. This facilitates PRVs to operate with a lower outlet pressure, which reduces AZP and leakage. DMAs can be aggregated into large zones for the majority of time. When the water company wishes to undertake leakage monitoring, the boundary valves can be automatically closed in order to revert the topology back to the original DMA structure
- By opening boundary valves, more independent supply paths between customers and sources exist. This improves the network resilience to failure by adding redundancy to the network. In the event of failure, boundary valves no longer need to be opened manually by the water company.
- Fewer dead ends in the network exist when some of the boundary valves are dynamically opened. This results in less dirty water accumulating in the network. The risk to water quality associated with the opening of boundary valves is eliminated.

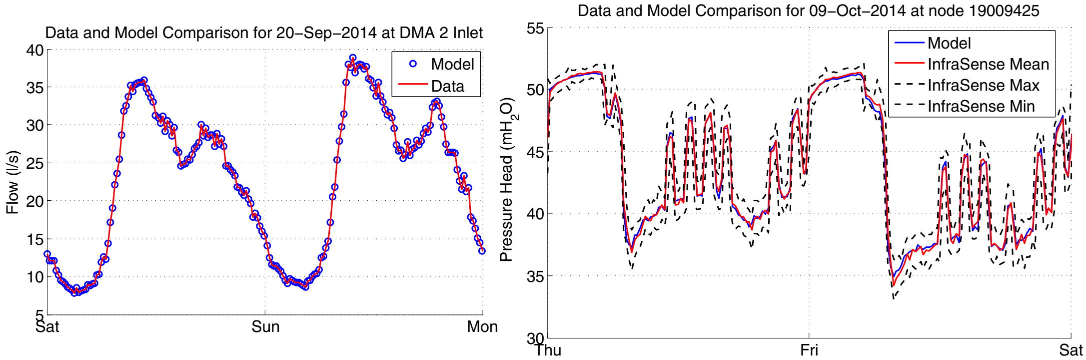
The installation of a dynamic topology on a network with DMAs involves the replacement of closed boundary valves with automatic self-powered control valves. The valves have advanced pilots for stem position and pressure/flow modulation, turbines for energy harvesting, insertion flow meters, remote communications, and high frequency (128S/s) pressure monitoring [10]. PRVs in the network are also fitted with this technology to provide optimal pressure and incident management on a network with dynamic zoning. A description of the installation and technology of a dynamic topology can be found in [9].

3. Experimental Facility and Methodology

We investigate the performance of the three pressure management approaches outlined in section 2 through the setup and operation of an experimental site set up on a real, operational network shown in Figure 1a. This figure also shows the network's elevation. The site is situated on two interconnected DMAs serving approximately 8,000 properties in total. When the network is operated as separate DMAs with a closed topology, each DMA has a single feed as shown in Figure 1a. The DMAs are separated by multiple closed boundary valves (BV). Two of these boundary valves are automatic control valves, called BV 1 and BV 2 in Figure 1a, which facilitate the operation of a dynamic topology. Each DMA has a separate critical point (CP), which is defined as the point of the DMA where pressure is closest to the minimum allowable pressure. For most nodes, the minimum allowable pressure has been set to $15mH_2O$, which facilitates aggressive leakage reduction whilst still maintaining minimum service levels. The DMAs also supply critical customers including two hospitals and a large industrial user. Two PRVs are located in the experimental programme, called PRV 1 and PRV 2 in Figure 1a. The precise network behaviour is captured by monitoring pressure at 128S/s using 18 Infrasense TS [10] loggers deployed in the network, as shown in Figure 1a.

The specific set up of the thee different network configurations is as follows:

- The operation of configuration 1 is as follows. The boundary valves BV 1 and BV 2 are closed at all times. The two DMAs are therefore not hydraulically connected. PRV 1 has a fixed outlet pressure of $30mH_2O$ which results in a pressure at CP 1 during peak demand hours of approximately $20mH_2O$. The minimum allowable pressure at this node is $15mH_2O$. The approximate buffer of $5mH_2O$ is to proivde the network with some additional resilience in the case of failure. As noted in the literature, excess pressure is one way to increase the network's resilience to failure [13].



(a) Flow (b) Pressure

Fig. 2: A comparison of modelled and measured pressure and flow at one of the InfraSense TS locations

- The operation of configuration 2 also has boundary valves BV 1 and BV 2 closed at all times. PRV 1 and PRV 2 follow a flow modulation look up table which was obtained using a hydraulic model and optimization method from [9]. The flow modulating PRVs results in a consistent pressure at CP 1 of approximately $15mH_2O$, which is the minimum allowable pressure. The network can operate closes to the minimum allowable pressure (unlike configuration 1) because flow modulating PRVs will react to some failure situations such as bursts and fire flow by increasing the outlet pressure due to the flow reading increasing.

- The operation of configuration 3 introduces a dynamic boundary. BV 1 and BV 2 open to 20% during the day, and automatically shut at night between 02:00-05:00 so that leakage monitoring practices can be undertaken. PRV 1 and PRV 2 also follow a flow modulation look up table derived in the same manner as configuration 2, however the look up tables are different due to the boundary valves introducing a change in flow regime. As before, flow modulation results in a consistent pressure at CP 1 of approximately $15mH_2O$.

The network performance for the different configurations is evaluated in terms of average zone pressure and resilience to failure. The AZP is calculated using a hydraulic model that is calibrated to a high degree of accuracy using the deployed pressure loggers and flow meter data. In near real-time, the demand patterns are updated according to the flow meter data. At boundary valves, flow that crosses DMAs is measured using a bidirectional electromagnetic flow meter, and modelled by closing the link and adding or subtracting the traversed flow at the boundary valve's connecting node. This produces a hydraulic model that agrees exactly with observed flow data as shown in Figure 2a. The friction factors in the hydraulic model are also calibrated to agree with pressure at all logged locations shown in Figure 1a. The hydraulic model agrees with all pressure data measurements to within the guidelines laid out by [14]. A comparison of logged pressure and modelled pressure is shown in Figure 2b. The data, logged at 128S/s, is plotted at 15 minute intervals. This facilitates a maximum and minimum bound to be plotted which represents the dynamic state of the network. The hydraulic model should always lie between these bands, and should be as close as possible to the mean data line. The majority of the hydraulic model was calibrated manually, although some parts of the model were calibrated using a random search algorithm. Other calibration methods in the literature include nonlinear programming [15] and evolution algorithms [16]. The automation of model calibration is an interesting problem, and the combination of real time data and instantaneous simulation of hydraulic conditions provides the foundations for more advanced forms of model calibration. This however is beyond the scope of this paper.

Using the calibrated hydraulic model, the AZP is calculated as follows:

$$AZP := \sum_{j=1}^{n_n} \omega_j p_j \tag{1}$$

where the coefficient ω is defined as:

$$\omega_j = \bar{L}^{-1} \sum_{i \in \mathcal{I}_j} \frac{L_i}{2}, \qquad \bar{L} = \sum_{i=1}^{n_p} L_i, \tag{2}$$

where p_j is the pressure head at node j, n_n is the total number of nodes, n_p is the total number of links, $\mathcal{I}_j$ is the set of indices for links incident at node j and L_i is the length of the i^{th} link.

The network's resilience to failure for different network configurations is tested experimentally by opening fire hydrants in the network. Three burst locations were selected as shown in figure 1a. Burst 1 starts at 09:00 and finishes at 12:00, burst 2 starts at 14:00 and finishes at 17:00, and burst 3 starts on the following day at 09:00 and finishes at 12:00. All bursts were created by opening a fire hydrant in the network as shown in Figure 1b. The flow rate was controlled to sustain $\sim 4.2l/s$ for all bursts. To increase accuracy in the modelling and analysis, the exact flow rate was recorded every 5 minutes and this data was added to the model as a separate demand profile for each burst.

4. Pressure Management Results

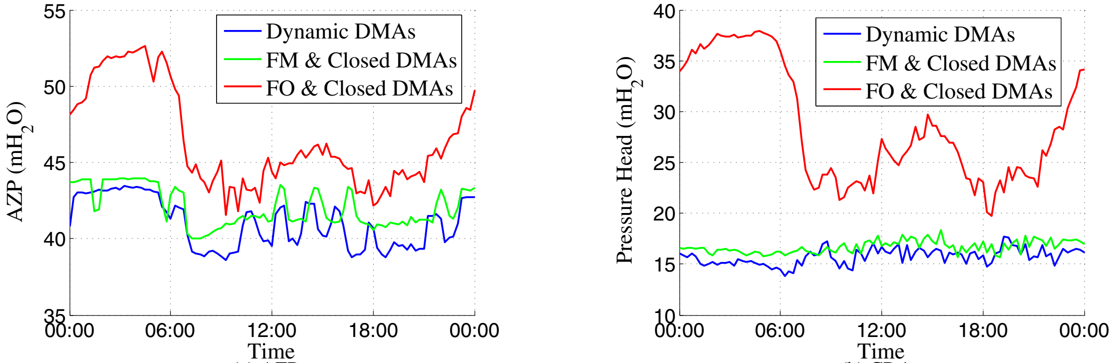
A comparison of AZP of the three pressure management configurations is shown in Figure 3a. The pressure at CP 1 for the same periods is also plotted in Figure 3b. We define daytime hours as 06:00-21:00 and nighttime hours as 21:00-06:00. The following observations are made:

- Fixed outlet PRVs and a closed DMA topology (configuration 1) results in a high AZP during times of low demand such as at night (night AZP = $49.7mH_2O$ compared with a daytime AZP = $44.5mH_2O$). This is also visible at CP 1, where the pressure at night is approx. $34.2mH_2O$ compared to peak demand hours where pressure sometimes reaches approximately $20mH_2O$. Peak demand hours in this network occur in the morning between 07:00 - 10:00 and in the evening around 18:00, at which times pressure at CP 1 drops closer to the minimum allowable pressure $15mH_2O$.

- The operation of a closed DMA topology and flow modulation PRVs with an optimized look up table for AZP minimization (configuration 2) produces a consistent pressure at CP 1 approximately equal to the minimum allowable pressure of $15mH_2O$. Since the PRV regulates pressure according to demand and therefore frictional energy losses in the network, AZP reductions are achieved at all times in comparison to configuration 1. These are most notable at low demand hour such as a night (night AZP = $43.1mH_2O$, which is a 13.3% or $6.6mH_2O$ reduction compared to configuration 1). During the day, AZP is $41.4mH_2O$, which is a reduction of 6.9% or $3.1mH_2O$ compared to configuration 1. At times of peak demand, these AZP reductions are minimal. This is because the fixed outlet pressure configuration is set up to ensure adequate pressure at peak hours, which is what a flow modulation system is designed to do at all hours. The occasional fluctuations in AZP in Figure 3a for configuration 2 are due to a valve on a nearby reservoir inlet opening and closing.

- The operation of a dynamic topology with flow modulating PRVs (configuration 3) also results in a consistent pressure at CP 1 approximately equal to the minimum allowable pressure (Figure 3b). However, during the day when the boundary valves are open, further AZP reductions are achieved in comparison to configuration 2 (a closed DMA topology and optimally controlled flow modulating PRVs). The daytime AZP for a dynamic topology is $40.2mH_2O$, which is a reduction of 3.1% or $1.3mH_2O$ over configuration 2. In theory, the night time AZP for configuration 3 should be equal to the AZP for configuration 2 when the boundary valves close at night. As seen in Figure 3b, it was not possible to achieve an identical pressure at CP 1. This results in a night AZP pressure for configuration of $42.5mH_2O$, which is $0.7mH_2O$ or 1.5% lower than the night AZP of configuration 2.

The operation of a dynamic topology had restrictions on the maximum opening percentage of the boundary valves for this initial investigation. The results shown are for a maximum boundary valve opening of 20%. In simulation, it is shown that reductions of up to 8.0% can be achieved when opening the boundary valves to 100% for this network (operating 2 PRVs and 2 boundary valves, see [9] for more details).



(a) AZP (b) CP 1

Fig. 3: A comparison of network configurations. (a) AZP (b)Measured (InfraSense TS) mean pressure head at CP 1 for different network configurations

5. Resilience Results

This section is split into two subsection. In the first, we describe the network behavior to the artificial bursts generated by opening fire hydrants in the network. In the second subsection, we describe and analyze a real burst event that occurred during the set up of the dynamic topology.

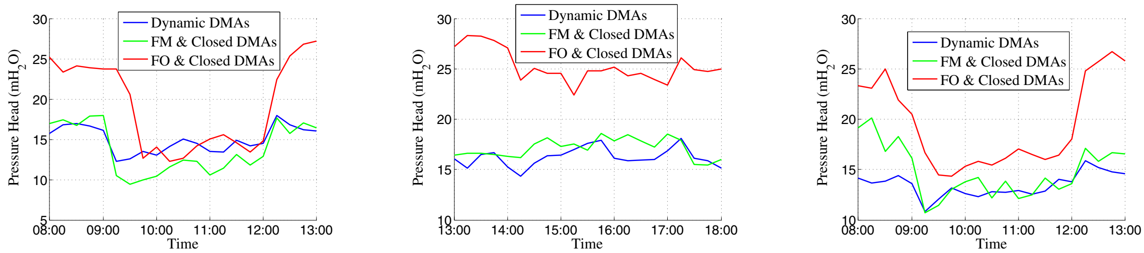
5.1. Artificial Bursts

The three artificially generated bursts are shown in Figure 4 by plotting pressure data at CP 1 for the three different network configurations. The following observations are made:

- Burst 1 is near CP 1 and hence is a critical burst location. Furthermore, the burst occurs between 09:00 - 12:00 which overlaps with peak demand hours, making the burst particularly critical during the first hour. For configuration 1 (fixed outlet pressure PRVs, closed DMAs), pressure drops substantially by $11.1mH2O$, from $23.8mH2O$ to $12.7mH2O$ and remains at this approximate pressure level for the duration of the burst until 12:00. This is because a fixed outlet PRV does not react to increases in demand. The start of burst 1 for configuration 1 was delayed because the water technician could not access the fire hydrant due to a parked vehicle, and the hydrant was finally opened at 09:20. Pressure during configuration 2 (flow modulating PRVs, closed DMAs) also becomes critical during burst 1, dropping by $8.6mH2O$, from $18.0mH2O$ to $9.4mH2O$. The pressure does recover slightly, increasing to levels between $10.6mH2O$ and $13.1mH2O$. Configuration 3 (dynamic topology) performs the best during burst 1. Pre-burst pressure is $16.1mH_2O$, and this drops by only $3.8mH_2O$ to $12.3mH_2O$. Pressure then recovers due to the flow modulating PRVs to levels between $13.0mH2O$ and $15.1mH2O$.

- Burst 2 is further upstream in the DMA within an area of high pressure and is therefore a less critical burst location. The burst was also carried out at non-peak demand hours (14:00 - 17:00). Configuration 1 drops from $27.1mH_2O$ to $23.9mH_2O$ and remains approximately at this pressure for the duration of the burst. Pressure at CP 1 is similar for both configuration 2 and 3. For configuration 3, pressure drops momentarily to $14.3mH_2O$ before returning above $15mH2_O$ for the remainder of the burst. No other pressure drops below $15mH_2O$ are observed.

- Burst 3 is in a less critical location than burst 1, but more critical than burst 2 due to its closer proximity to the critical point. The burst also occurs between 09:00 - 12:00, making the first hour particularly critical. For configuration 1 (fixed outlet pressure PRVs, closed DMAs), pressure drops substantially from $20.5mH_2O$ to $14.5mH_2O$. Pressure recovers slightly due customer demand reducing after peak-demand hours. At the end of the burst (12:00), pressure increases to $25mH_2O$. For configuration 2 (flow modulating PRVs, closed



(a) Burst location 1 (b) Burst location 2 (c) Burst location 3

Fig. 4: Artificially generated bursts produced by operating fire hydrants under different network configurations

DMAs), pressure drops from $16.1 mH_2O$ to $10.7 mH_2O$. A small recovery in pressure is made since the flow modulating PRVs react to demand increases, and pressure averages $13.3 mH_2O$ for the duration of the burst. For configuration 3 (dynamic topology), pressure at the CP on this day was being maintained slightly lower than $15 mH_2O$ before the burst occurred. To ensure a fair test, ideally pressure at CP 1 would have been higher than this during normal operation. Nevertheless, the burst was created at 09:00 and pressure dropped from $13.6 mH_2O$ to $10.8 mH2_O$ and then recovered due to the flow modulating PRVs, averaging at $12.9 mH_2O$. for the remainder of the burst. This is similar performance to configuration 2, despite operating pre-burst with a lower pressure at the critical point.

5.2. Real Burst Event

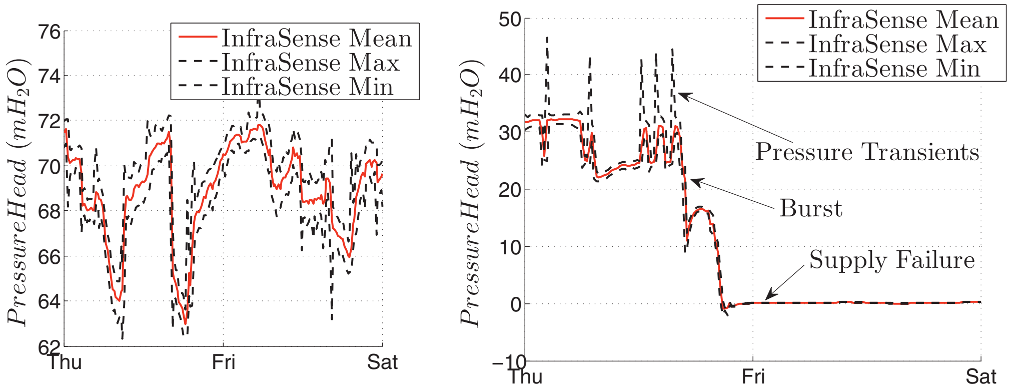
A real, major burst occurred upstream of DMA 2 on a 35 inch trunk main during the experimental investigation which resulted in a supply failure to DMA 2. This event was detected by the high density of logging equipment in place in the experimental programme. For example, the inlet pressure head at DMA 2 is plotted in Figure 5b. Prior to the burst, a number of periodic pressure transients are captured with fluctuations of approximately $20 mH_2O$. These transients occur as a result of an electronically operated valve opening and closing at the inlet of a nearby reservoir, upstream of DMA 2. The burst occurs at approximately 17:00 and the pressure drops to zero at the inlet of DMA 2 (Figure 5b). The inlet to DMA 1 was unaffected by the burst (Figure 5a).

At the time of this incident, the dynamic topology was in partial operation, with boundary valve (BV) 1 opening during the day and closing at night for leakage detection practices, and BV 2 closed at all times. The dynamic topology maintained the supply of water to 1,400 properties that would otherwise have been without water because DMA 1, which was fully operational, was able to supply DMA 2 through boundary valve BV 1.

An overview of the network pressure is shown in Figure 6a during the real burst incident. The flow at BV 1 is plotted in Figure 6b. The boundary valve is closed during the early hours of Thursday to measure the minimum night flow and undertake leakage localization. The boundary valve then opens at 06:00, ready for the increase in consumption throughout the day. During the morning peak, optimal pressure management is maintained by supplying DMA 1 from DMA 2, as indicated by the positive flow at BV 1 in Figure 6b. The real burst then occurs later that day at 17:00. The flow at BV 2 is now negative, indicating that DMA 1 is supplying DMA 2. At night, BV 1 is kept open. Demand decreases and the flow drops to approximately $1 l/s$. The following day, DMA 1 continues to supply DMA 2 via BV 1 with a flow of approximately $8 l/s$ for 1,400 properties that would otherwise have been without water unless a manual intervention was carried out.

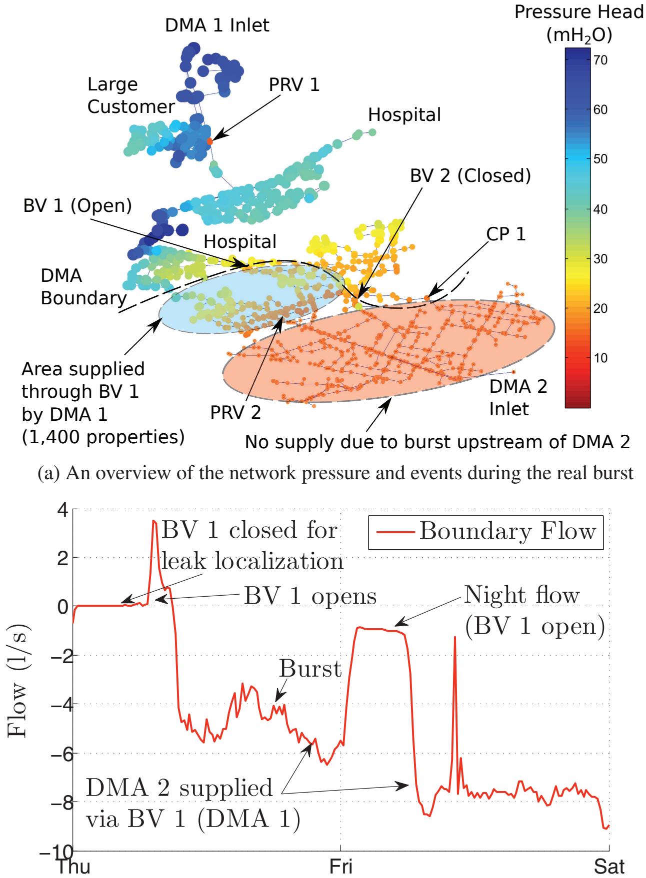
6. Conclusion

This paper has carried out an extensive experimental investigation into the operation of water distribution networks under three different configurations. These include fixed outlet pressure reducing valves (PRV) operating on a closed DMA topology, flow modulating PRVs operating on a closed DMA topology, and flow modulating PRVs operating with a dynamic topology. The investigation includes an analysis of average zone pressure (AZP) as well as resilience



(a) DMA 1 Supply (b) DMA 2 Supply

Fig. 5: A comparison of DMA 1 and DMA 2 inlet pressure heads during the occurrence of a real burst



(a) An overview of the network pressure and events during the real burst

(b) Boundary flow at BV 1

Fig. 6: (a) An overview of the network during the real burst incident. The top DMA, which was not affected by the burst, supplies the neighbouring DMA with an alternative supply of water (b) the boundary flow at BV 1 which supplies the affected DMA

to failure. In order to capture the precise network behavior, 18 pressure sensors logging at 128S/s were installed. A calibrated hydraulic model was used to estimate the AZP. Artificial bursts were generated by operating fire hydrants in order to test the network's resilience to failure.

The operation of fixed outlet PRVs on a closed DMA network results in a substantial excess of AZP at non-peak demand hours. A network operating with closed DMAs and fixed outlet PRVs also suffered severe drops in pressure during the artificial bursts. A network operating with flow modulating PRVs and a closed DMA topology substantially reduced the AZP during the night by 13.3% during the night and 6.9% during the day. Improvements in the resilience to the artificial bursts was also observed compared to fixed outlet PRVs. This is due to the fact that flow modulating PRVs increase the outlet pressure when demand increases. The operation of a dynamic topology further reduced the AZP by 3.1% over a closed DMA topology and flow modulating PRVs. The artificial bursts reduced pressure in the network the least when a dynamic topology was in operation due to the additional supply paths available.

In addition to the planned experimental investigation, a real burst on a major trunk main resulted in thousands of customers being left without a water supply. During this event, the dynamic topology successfully kept 1,400 properties in service that would otherwise have been without water by providing a supply route via a neighbouring DMA

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